

Climb Trajectory Prediction Software Validation for Decision Support Tools and Simulation Models

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The Next Generation Air Transportation System (NextGen) is the solution to capacity, safety, and efficiency problems that will result from an expected increase in traffic. Trajectory-based operations are identified in the NextGen Concept of Operations as a key capability required to ensure the success of NextGen; thus, it is essential that the accuracy of trajectory prediction software be tested and validated for all phases of flight. Trajectories are also modeled in fast-time simulation tools that are used to test future NextGen concepts and identify possible benefits or problems. The objective of this testing activity is to identify outliers during the climb phase of flight in the trajectory predictions of two decision support tools as well as in the trajectory modelers of two fast-time simulation models. The errors in trajectory prediction will also be examined by aircraft type in order to measure the accuracy of aircraft characteristics utilized in the tools.

1. Introduction

Air traffic in the United States is predicted to increase three times by the year 2025. The Next Generation Air Transportation System (NextGen) is the solution to capacity, safety, and efficiency problems that will result from this increase. The Federal Aviation Administration (FAA) is primarily responsible for the implementation of NextGen. The NextGen Concept of Operations identifies aircraft trajectory-based operations as a key capability required to ensure the success of NextGen. Four-dimensional (4-D) trajectory prediction algorithms predict an aircraft's horizontal and vertical position at some time in the future and are used for conflict detection, metering, and other applications in air traffic management decision support tools (DSTs). Fast-time simulation models also utilize 4-D trajectory modeling in research and development of new NextGen concepts. Therefore, it is essential that the accuracy of trajectory prediction software be tested and validated.

There are three phases of flight: climb, cruise, and descent. Recent NASA analyses have shown that changes in an aircraft's phase of flight are associated with higher trajectory prediction errors as compared to cruising at a steady altitude. It has also been shown that errors in climb trajectory prediction differ among aircraft types (Gong and McNally 2004).

The objective of this testing activity is to identify the trajectory accuracy outliers produced during the climb phase of flight by various aircraft types and other factors. Archived air traffic data from the Washington, D.C. Air Route Traffic Control Center (ARTCC) is utilized to compare the accuracy of trajectory predictors used in DSTs such as User Request Evaluation Tool (URET) and En Route Automation Modernization (ERAM), as well as those used in fast-time simulation models such as Airspace Concept Evaluation Simulation (ACES) and Reorganized Air Traffic Control Mathematical Simulator (RAMS).

DSTs aid air traffic controllers in making the safest and most efficient decisions in moving aircraft. URET was developed to help air traffic controllers safely handle a greater number of user-preferred flight profiles, increase flexibility, and increase system capacity (The MITRE Corporation 2008). ERAM combines the functionality of URET and the Host Computer System and provides the ARTCCs with surveillance and flight data processing, conflict probe functionality, and display support for the National Airspace System (Federal Aviation Administration 2007). At the heart of these critical systems is the accuracy of trajectory predictions. Thus, analysis techniques to easily identify errors in the modeling of aircraft trajectories will help ensure these systems meet their goals of improved safety and efficiency.

Fast-time simulation is used in the validation of new concepts to obtain an understanding of potential benefits or problems. ACES is an agent-based fast-time simulator developed by NASA to "enable evaluation of the system-wide effects of proposed air transportation concepts intended to reduce delay, increase capacity, and accommodate the forecasted growth in air traffic" (National Aeronautics and Space Administration 2007). RAMS is developed and supported by ISA Software and features 4-D flight profile calculation, 4-D sectorization, and 4-D

spatial conflict detection and resolution (ISA Software 2008). Similar to the URET and ERAM operational systems, these simulation models also require trajectory predictions to be timely and accurate. The methods developed in this paper will identify possible outliers in their trajectory modeling.

2. Overview of Data and Preparation

This activity focused on the accuracy of the trajectories created by DSTs and simulation models during the initial climb phase of flight. Thus, extensive data preparation was required to filter traffic data to only include flight tracks before their tops of climb were reached and to convert the recorded data to formats compatible with ACES and RAMS.

A. Base Scenario

Recorded en route air traffic from the Washington Air Route Traffic Control Center (ARTCC), referred to as ZDC, was utilized in this study. The recorded ZDC data was collected on March 17, 2005 and contained approximately five hours of flight data and approximately 2,200 flights. Using this recorded data, two scenarios were created to generate input files for URET and for ERAM test runs. For URET, this consisted of a single file containing Air Traffic Control (ATC) and track messages. This file was formatted into an ASCII pipe delimited version of the Host Computer System (HCS) Common Message Set (CMS) (WJHTC/AOS-300 2004). This ASCII version of the CMS was developed during the URET Testing Program. For ERAM, the input scenarios consisted of two files, one containing ATC messages and the other containing the radar target message. A mode of the ATCoach simulator was invoked that reads the ATC clearances in one file and the radar data in a separate file, injecting them into ERAM and emulating the operational data flow (UFA 2004). The two scenarios are slightly different due to the different methods of formatting the recorded data into appropriate URET and ERAM scenarios. These two test scenarios were originally created for ERAM's formal Run-For-Record (RFR) Flight Data Processing/Conflict Probe Tool Accuracy Test in August 2007 and were recycled for this experiment.

Since this paper focuses on studying trajectory accuracy during the climb phase of flight, the scenarios were truncated to only include aircraft that were departing in both scenarios. Of the original 2,200 flights, 627 departure flights were analyzed in this study. This filtering was performed after the scenarios were executed by their respective systems; only during the analysis of the results were flights removed.

B. Trajectory Predictions of the Decision Support Tools

Once the air traffic scenarios are injected into URET and ERAM, the predictions need to be captured and input into the various test tools for analysis. In order to compute the accuracy of any trajectory prediction, two datasets are needed: (1) the true (actual) flight paths, and (2) the trajectory predictions. In this study, the actual flight paths are derived from the recorded air traffic stored in CMS format. Both URET and ERAM have their own system analysis recording (SAR) capabilities. The SAR is where predicted flight paths are stored. The binary files that are produced are parsed with a set of scripts. This produces a trajectory file containing one or more 4-D trajectory predictions for every aircraft in the form of a sorted listing of the trajectory's predicted positions in time, stereographic x-y coordinates, altitude, and ground speed.

C. Preparation for Simulation Tools

RAMS and ACES are fast-time simulators that model aircraft flight paths. These tools simulate aircraft using a set of positional data, normally latitude and longitude coordinates. The tools generate a 4-D flight trajectory for every flight of a given air traffic scenario. The flight trajectories are created based on the input data and procedures specific to the individual tool; hence, they are often different between models. Since our study focuses on how close to actuality the models simulate the aircraft during the climb phase of the flight, the input flight paths for the simulation tools are created using the recorded data described in Section 2.A.

The scenarios needed to be prepared prior to injecting them into the models. The points of vertical transition in the scenario track data were calculated to define the time, speed, latitude and longitude coordinates, and altitude of each vertical event. A vertical event is a transition in the vertical profile from one vertical phase of flight to another. The three vertical phases of flight are level, ascending, and descending. Figure 1a illustrates a flight with four vertical events where the x-axis is time and the y-axis is the altitude of the aircraft. Furthermore, at time t_2 an ascent-to-level event occurs, at t_3 a level-to-ascent, t_4 is an ascent-to-level, and t_5 is a level-to-descent.

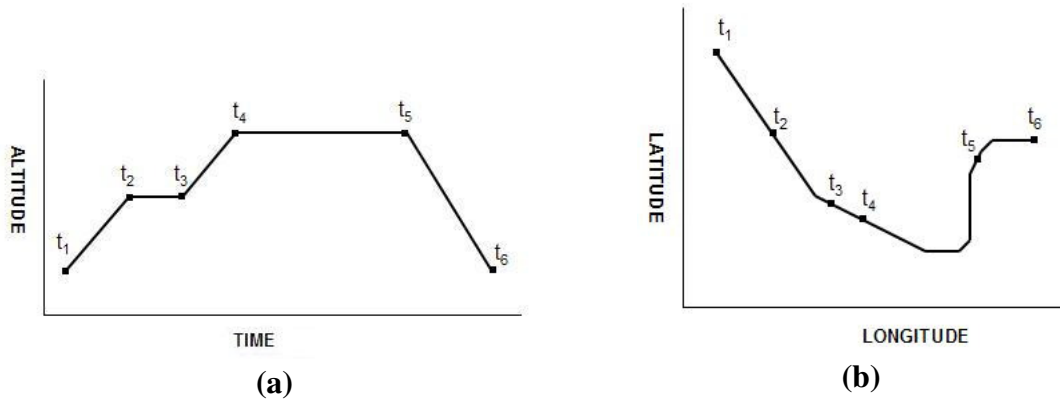


Figure 1: Vertical and Horizontal Views of Vertical Events

As previously mentioned, the simulations' tools use a set of horizontal coordinates to model the aircraft flight paths. In addition to the starting and ending coordinates denoted in Figure 1a by t_1 and t_6 , respectively, the latitude and longitude coordinates at the time of each vertical event were used to produce the input air traffic. An example of the horizontal profile is presented in Figure 1b. The altitude and time at each vertical event is utilized in the model as well. The tools use this information to model the flights and generate their own vertical profile. This profile may deviate from the original inputted air traffic, which was based on actual operational data; thus, this study focuses on measuring the amount of these differences.

Once the tools are executed, a 4-D trajectory is created for every flight. These trajectories are extracted into a trajectory file, which will be processed to measure the accuracy of the simulated trajectory when compared to the actual flight paths.

3. Trajectory Prediction Accuracy Measurement

Trajectories are generated by the trajectory predictor (TP) that resides within a DST or by the trajectory modeler (TM) within a simulation tool. In DSTs, trajectories are used to alert air traffic controllers of potential conflicts in the future. Trajectories in simulation tools function as flight paths used to examine the effects of new airspace concepts. The accuracy of a TP or TM determines its overall performance. Measuring the accuracy of a TP or TM requires the actual flight paths as well as the flight paths' predicted trajectories or modeled trajectories. In order to measure the accuracy, the difference in altitudes of the actual and predicted or modeled paths is calculated. The details of these steps are described below.

A. Measuring Vertical Trajectory Prediction Accuracy

Trajectory prediction accuracy is measured by the difference between the trajectory predictor's path and the actual path flown by the aircraft. In order to measure this difference, the actual path of the aircraft needs to be obtained by examining radar surveillance reports and other air traffic control (ATC) data such as flight plan amendments and altitude clearances. A set of data reduction and analysis tools are used to validate, synchronize, and store the data into database tables. Then another software tool is used to compare the inputted trajectories against the actual flight paths and calculate a set of metrics, quantifying the accuracy of the trajectory predictions, which is stored in another database table. The key metric in this study is the vertical error. Vertical error is the difference between the trajectory's predicted altitude versus the actual track altitude (Paglione and Oaks 2007). Figure 2 illustrates these two positions and the vertical error. The track altitude is labeled TK while the trajectory altitude is labeled TJ in the figure. A positive vertical error occurs when the trajectory's altitude is below the actual track altitude; hence, the error is negative when the trajectory's altitude is above the track altitude. The errors are explored using descriptive and inferential statistics acquired by a statistical software package.*

B. Interval Based Sampling

There are two parts in considering the accuracy performance trajectory predictions generated by DSTs. The first is the accuracy of a trajectory predicting the present position of an aircraft and, secondly, the accuracy of a

* JMP is developed by the SAS Institute and used here for all statistical calculations, see www.jmp.com for details.

trajectory predicting the future position of an aircraft; both are extremely important in the conflict resolution process of an ATC.

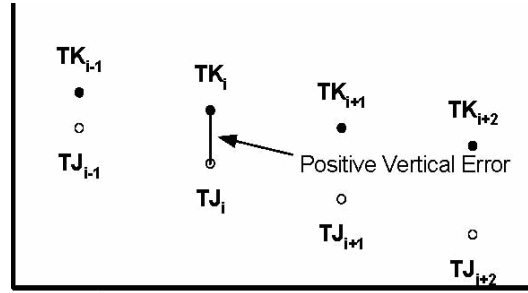


Figure 2: Vertical Trajectory Error

Interval Based Sampling Technique (IBST) is the trajectory accuracy sampling method developed by the Conflict Probe Assessment Team (CPAT) at the FAA William J. Hughes Technical Center and has been used in many FAA studies and test programs such as the Center TRACON Automation System and URET (Paglione and Oaks 2007). There are two main steps to the IBST. First, track points of an aircraft are sampled in succession a parameter number of seconds until the end of the track (see T_s in Figure 3). Then the trajectories are searched to find the most recent at a given sample time. Once the active trajectory is selected, the error in the trajectory is calculated iteratively for every look ahead time value specified by the user. For the DSTs, a sample time of 120 seconds and look ahead times of 60-second intervals from 0 to 900 seconds were used for this analysis. For the simulation portion of this study, a sample time of 10 seconds and no look ahead times were used. Since there is only one trajectory for each aircraft modeled in the simulation tools, look ahead time was not considered; however, sample time frequency was increased. With the combination of sample time (present time) and look ahead time (future time) IBST creates data that can be evaluated to study the accuracy of trajectory predictions at current and future states.

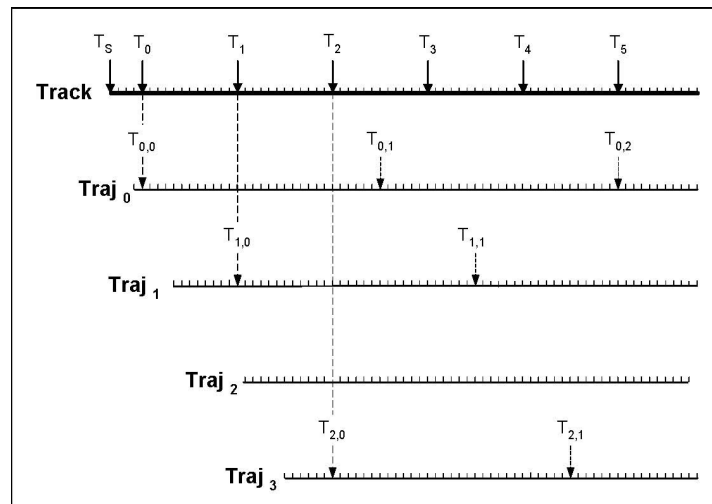


Figure 3[†]: Time-line for the Interval Based Sampling Technique

4. Results

The results of this testing activity are measured by vertical error and by the absolute value of vertical error. Vertical error accounts for the direction and magnitude of the error while its absolute value only provides the magnitude.

[†] Figures 2 and 3 have been adapted from the 2007 paper "Implementation and Metrics for a Trajectory Prediction Validation Methodology" by Paglione and Oaks.

The following standard statistical measures will be referenced in presenting the results: the mean discussed is the arithmetic mean which is the sum of the values divided by the number of values; the standard deviation is a measure of the variance of a set of data from its mean; the median is the middle of a distribution such that half of the values in the data set are above the median and half are below; and N is the number of error measurements in the data set. When the means of vertical error are discussed, it is the mean absolute value of vertical error that is being referenced since it more accurately illustrates the average magnitude of error.

A. Decision Support Tools Vertical Error

Initially, it was expected that the vertical errors of the DST ERAM would be less than those of URET. It is, in fact, a design requirement for ERAM to be at least as accurate as URET. Since several minor algorithmic enhancements were made in ERAM, most notably an improved radar tracking system, we intuitively expected the trajectories of ERAM to be more accurate than those of URET.

Results of the URET analysis indicated that it contained, on average, moderate vertical error that was somewhat balanced above and below the actual altitudes (see Table 1). The maximum vertical error for URET was 26,000 feet, and the mean vertical error for URET was 1777.19 feet. A median error of -42 feet indicated slightly more error occurring above the true altitudes; in other words, there was marginally more error when the trajectory's altitude was above the actual altitude than there was when the trajectory was below the actual track.

The analysis of ERAM yielded similar results (see Table 2). The maximum vertical error was 25,941 feet, and the mean error for ERAM was 1873.15 feet. The median vertical error was 0 which suggested the same amount of error existing above and below the actual track altitudes.

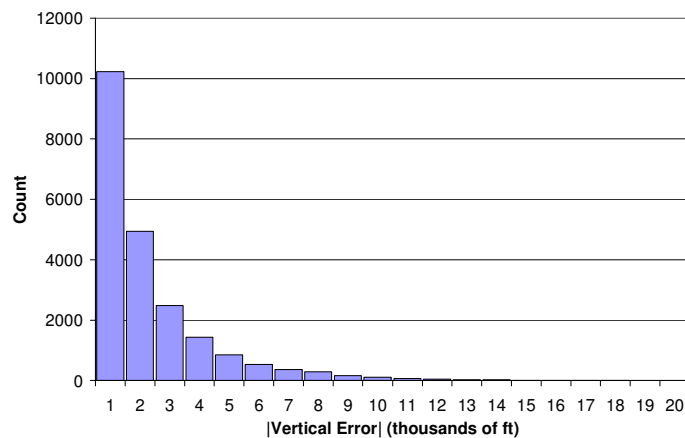


Figure 4. Histogram of Absolute Vertical Error for URET

Absolute Vertical Error	Value
Mean	1777.19
Standard Deviation	2190.48
Minimum	0
Maximum	26000
Median	1000
N	30233

Table 1. Vertical Error Statistics for URET

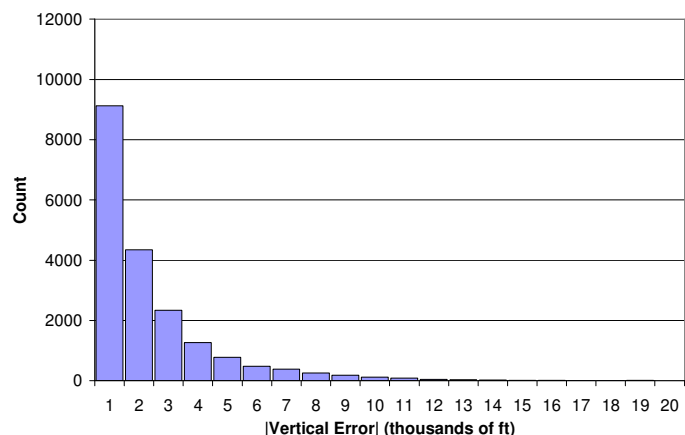


Figure 5. Histogram of Absolute Vertical Error for ERAM

Absolute Vertical Error	Value
Mean	1873.15
Standard Deviation	2320.11
Minimum	0
Maximum	25941
Median	1017
N	26494

Table 2. Vertical Error Statistics for ERAM

As can be seen from the histograms in Figures 4-5, the distribution of vertical error in URET is similar to that of ERAM. Comparing the mean vertical errors of URET and ERAM, it is concluded that the trajectories of URET are slightly more accurate than those of ERAM during the initial ascent to the top of climb. However, the median absolute vertical error of ERAM is very close to that of URET (within 20 feet), which indicates possible outliers in ERAM that caused the mean error to be high. Therefore, ERAM does not contain significantly more vertical error than URET.

Figure 6 shows the mean vertical error by look ahead time for URET and ERAM. For each look ahead time value, ERAM had a higher mean vertical error than URET. The graph confirms the statistics which show that ERAM and URET had very similar errors, but ERAM has slightly more error than URET. It is interesting to note that for both ERAM and URET, mean vertical error and look ahead time seem to have an exponential relationship based on the shape of the plot.

A comparison was also conducted on the errors of URET and ERAM based on aircraft type. This analysis was done on only those aircraft types that were found in output from both tools; thus, the comparison was performed based on 91 different aircraft types. Figure 7 below shows the frequency of flights in URET and ERAM for each aircraft type, and Figure 8 shows the mean absolute vertical error for each aircraft type in URET and ERAM. It is clear from the histograms that those aircraft types with high vertical errors did not occur frequently in the scenario, and those aircraft types that had a high frequency did not contain high vertical errors.

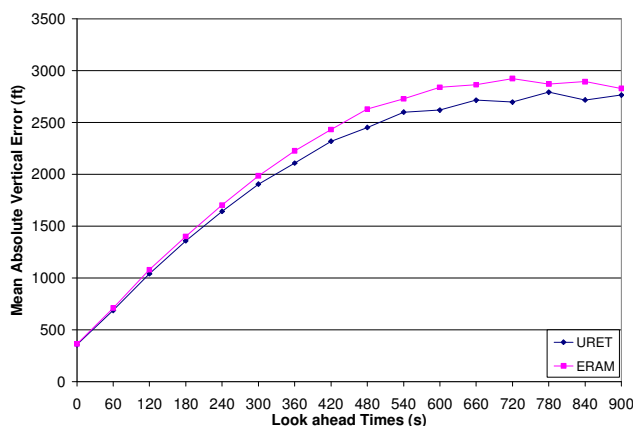


Figure 6. Plot of Mean Vertical Error by Look ahead Time

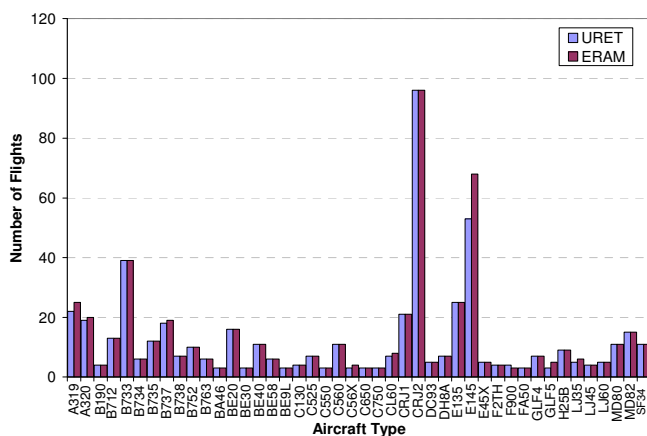


Figure 7. Histogram of Frequency of Flights by Aircraft Type in URET and ERAM

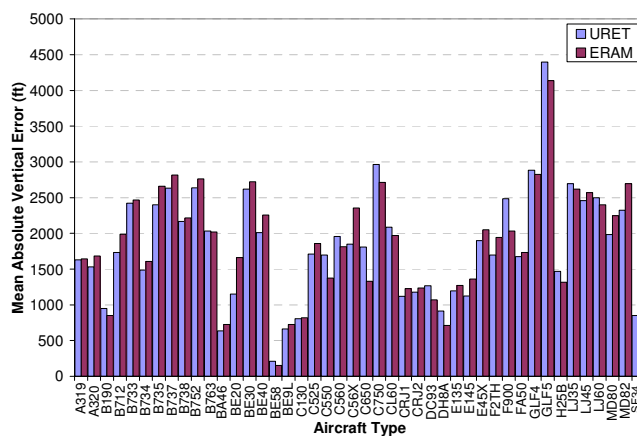


Figure 8. Histogram of Mean Absolute Vertical Error by Aircraft Type in URET and ERAM

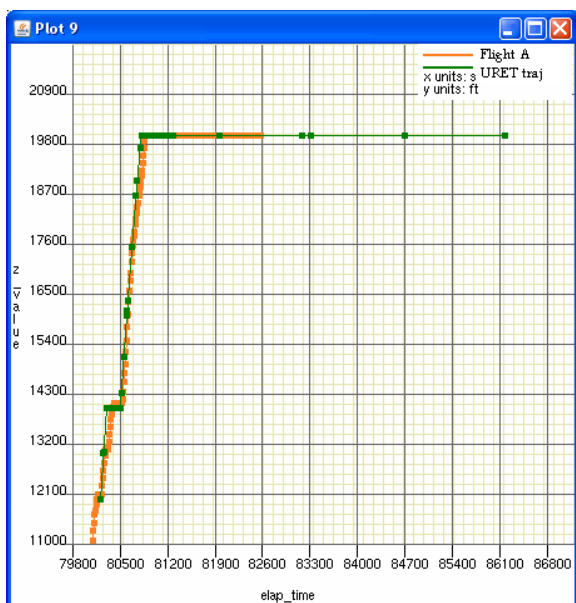


Figure 9: Time vs. Altitude Plot of Flight A and its URET trajectory

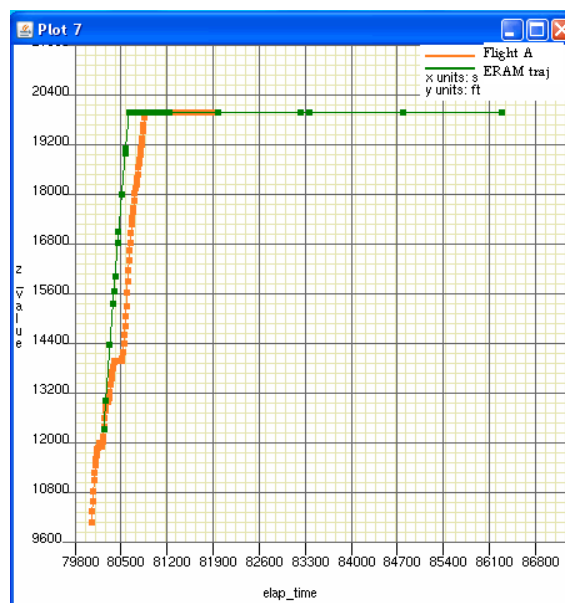


Figure 10: Time vs. Altitude Plot of Flight A and its ERAM trajectory

A simple difference measure was taken for the mean vertical errors of URET and ERAM for each aircraft type (URET error – ERAM error). It was determined that ERAM had a higher mean error for almost 59% of the aircraft types. Of these cases where ERAM had higher error, the average difference between URET and ERAM errors was approximately 277 feet. When URET had higher error, the average difference was approximately 233 feet. This difference, although it may have been statistically significant, does not rise to the level of practical significance. For example, the aircraft's altitude data is only supplied to the nearest 100 feet. Thus, any difference less than 100 feet is not significant; thus, it can not be concluded that URET and ERAM were systematically different.

Above is an example of a flight that was in both URET and ERAM. This flight contained one level period prior to reaching its top of climb; however, URET captured this level period while ERAM did not. Figure 9 shows the flight's altitude as a function of time in URET, and Figure 10 shows the same information in ERAM. If ERAM had predicted the level phase of this flight, then URET and ERAM would have had minimal difference in vertical error for this flight.

B. Fast-time Simulation Tools Vertical Error[‡]

Only flights with one continuous ascent to its top of climb were modeled in ACES due to its inability to model interim altitudes. Thus, it was expected that the output of ACES would also include only continuous ascents. However, ACES forced all of the flights to have at least one level phase before reaching its top of climb (see Figure 11 below for an example). The level phase usually occurred at or near an altitude of 10,000 feet.

The additional level period in the ACES trajectories caused its errors to be very high. The maximum vertical error for ACES was 30,000 feet while its mean error was 8,195.1 feet. In charts such as Figure 12, which plot the actual aircraft trajectory with the ACES trajectory, it appears that if the level period was not modeled in ACES, the errors would be much less. The median of the vertical error for ACES was 6,900 feet, which along with the histogram in Figure 12 below, indicates that the majority of the vertical errors occurred when the ACES trajectory was lower than the actual flight. This makes sense since the level period of ACES caused its trajectory to remain at a low altitude while the actual flight continuously ascended to its top of climb.

[‡] Testing was performed on RAMS version 5.29.06 and ACES version 510_v4.

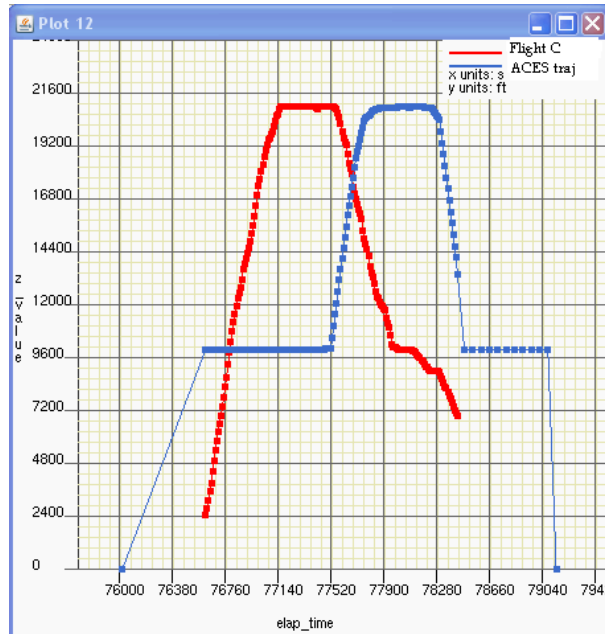


Figure 11: Time vs. Altitude Plot of Flight C and its ACES trajectory

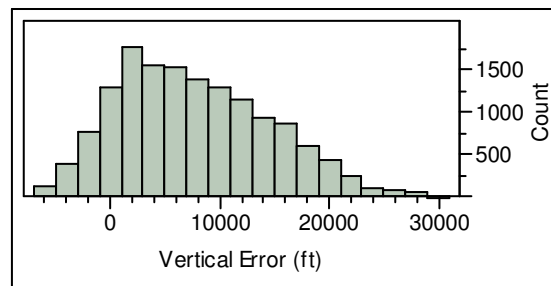


Figure 12: Histogram of Vertical Error for ACES

On the other hand, RAMS was able to model flights with continuous ascents as well as those which contained interim altitudes. The step climbs were modeled by creating NAVAIDS at each location where a vertical event occurred (these are explained in Section 2.C) and instructing RAMS to reach each NAVAID at a required altitude.

Overall, results show that our expectations were met, and RAMS had minimal error. The maximum vertical error for RAMS was 13,038 feet, and the mean vertical error for RAMS was 1,807.6 feet. Its median vertical error was 0 feet, indicating an even distribution of error above and below the actual track.

In order to compare the two simulation models, the flights modeled by ACES needed to be extracted from RAMS since more flights were modeled in RAMS than in ACES. As stated above, the mean error for ACES was 8,195.1 feet. The mean error for RAMS flights that were also in ACES was 1,775.5 feet. Figures 13-14 and Tables 3-4 below also show that the errors for RAMS were much smaller than the errors for ACES.

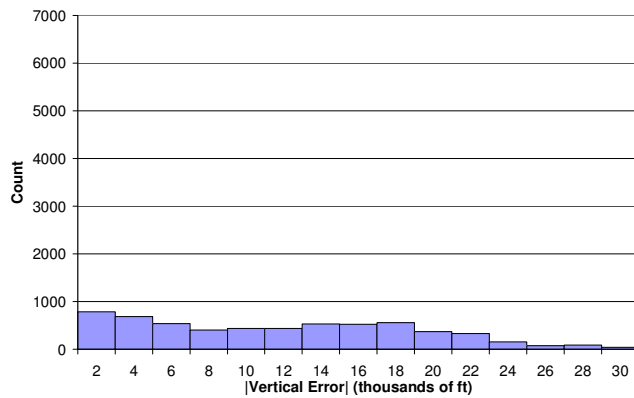


Figure 13. Histogram of Vertical Error for ACES

Absolute Vertical Error	Value
Mean	8195.1
Standard Deviation	6277.09
Minimum	0
Maximum	30000
Median	6900
N	14857

Table 3. Vertical Error Statistics for ACES

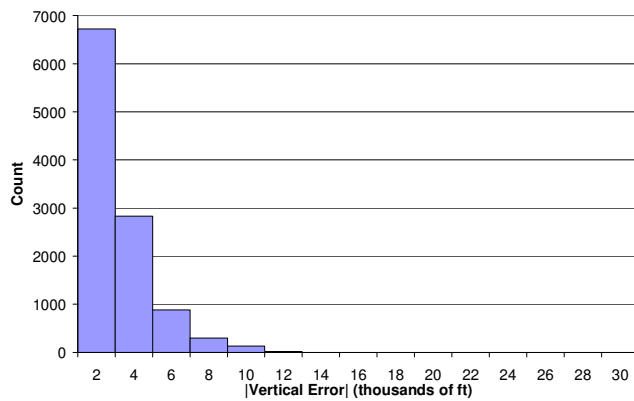


Figure 14. Histogram of Vertical Error for RAMS

Absolute Vertical Error	Value
Mean	1775.48
Standard Deviation	1705.45
Minimum	0
Maximum	10991
Median	1295
N	14857

Table 4. Vertical Error Statistics for RAMS

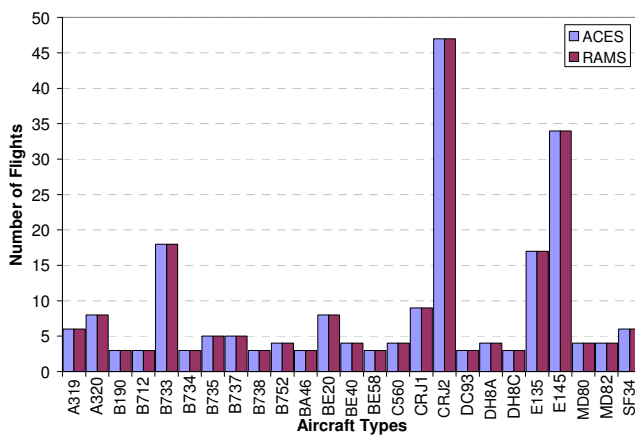


Figure 15. Histogram of Frequency of Flights by Aircraft Type for ACES and RAMS

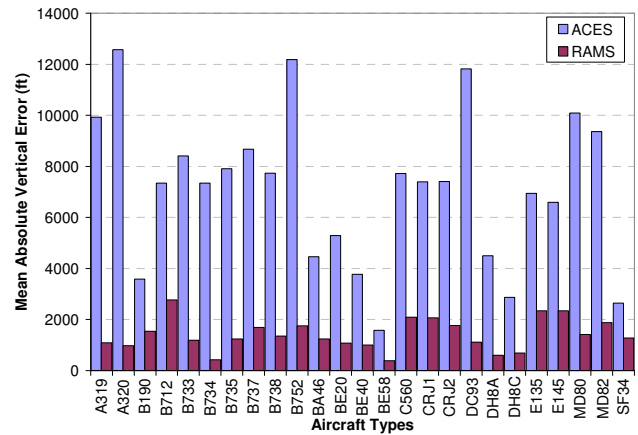


Figure 16. Histogram of Mean Absolute Vertical Error by Aircraft Type for ACES and RAMS

The output of RAMS and ACES had 66 aircraft types in common. Figure 15 shows the number of flights for each aircraft type for ACES and RAMS. Figure 16 shows the mean absolute vertical errors for each aircraft type in ACES and RAMS. These figures show that aircraft types which occurred frequently in the scenario had low vertical errors, and those with high vertical errors occurred very infrequently.

Results of the comparison of RAMS and ACES based on aircraft type showed that the mean absolute vertical error for ACES was higher than that of RAMS for 100% of the aircraft types. The average difference between RAMS and ACES errors was 6,109.4 feet. This is undoubtedly due to the error in ACES caused by the forced level period of each flight. It is thought that the difference between RAMS and ACES would be much smaller if ACES did not create the level periods.

Figures 17-18 show the ACES and RAMS trajectories for one flight. The flight's actual track had one continuous climb from about 7,000 feet to about 16,000 feet. Figure 17 shows that the ACES trajectory began at ground level then climbed to about 10,000 feet where it leveled off. The ACES trajectory finally finished its climb to slightly below the flight's top of climb altitude. As is evident when comparing the charts, RAMS was much more accurate than ACES in the vertical climb of this flight. The RAMS trajectory closely followed the actual track during the ascent to the top of climb.

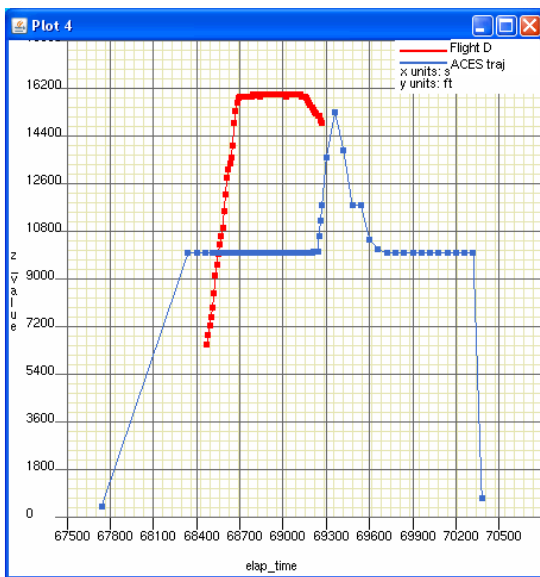


Figure 17: Time vs. Altitude Plot of Flight D and its ACES trajectory

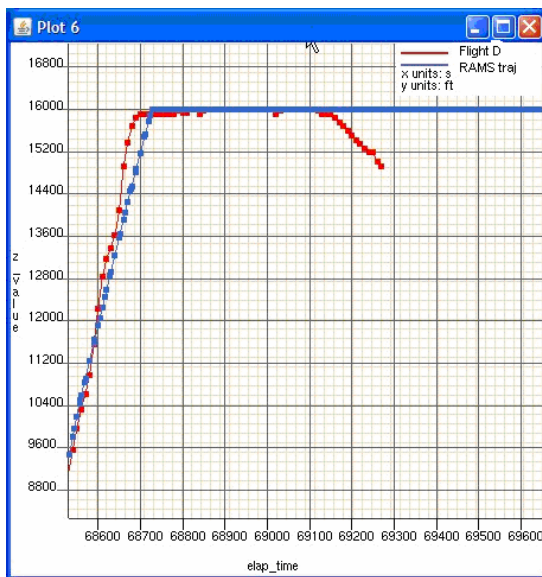


Figure 18: Time vs. Altitude Plot of Flight D and its RAMS trajectory

C. Top of Climb Time Error

For each of the tools, the trajectories did not always reach the top of climb (TOC) altitude at the same time as the actual flight. Figure 19 depicts one scenario where the trajectory reaches the TOC altitude before the actual flight and explains the calculation of the time error. The time error is the absolute value of the difference in time of when the trajectory reached the TOC altitude and when the flight reached the TOC altitude.

Table 4 shows the mean, median, minimum, maximum, and standard deviation of the absolute value of time error. The means and medians of the time error followed an expected trend based on knowledge of the tools. ERAM and URET had similar low to moderate errors where ERAM was slightly more accurate than URET. The mean and median time errors of RAMS were also similar to those of the DSTs. Finally, as a direct result of the forced interim altitudes, ACES had very high error statistics.

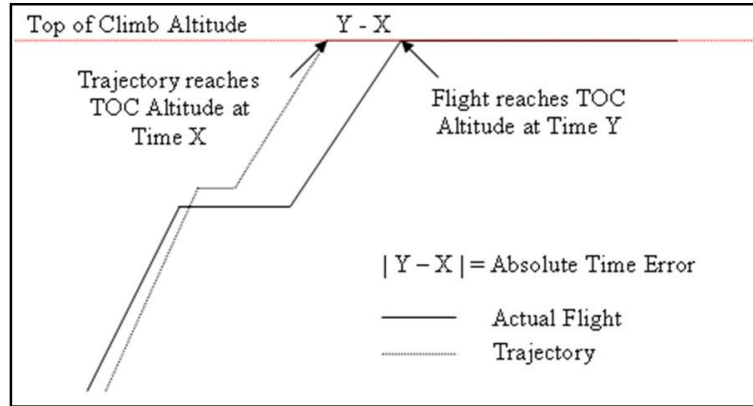


Figure 19. Top of Climb Time Error Diagram

Absolute Time Error	URET	ERAM	ACES	RAMS
Mean	357.4333	234.7464	882.379	221.4544
Median	143	120	820	136
Minimum	0	0	270	0
Maximum	11097	4650	10240	1749
Standard Deviation	639.9931	355.8754	666.8139	266.2661

Table 4. Time Error Statistics for all four tools (s)

5. Conclusion

The objective of this study was to test the accuracy of the trajectory predictor/modeler software during the ascent to top of climb in DSTs URET and ERAM as well as in fast-time simulation models ACES and RAMS. Also, it is important to note that while the DSTs function as predictors of aircraft trajectories, the simulation tools do not make predictions; instead, they model the aircraft's flight path. After track data from ZDC was filtered, flagged for vertical events, and translated into ACES and RAMS format, a statistical software tool (JMP©) was used to obtain the means and medians of the vertical error and absolute value of vertical error for each system.

It was found that URET and ERAM both contained a moderate amount of vertical error. The mean vertical error for URET was 1,777.19 feet, whereas ERAM had a slightly higher mean vertical error of 1873.15 feet. The medians of absolute vertical error, though, indicate that ERAM is as accurate as URET. In a comparison by aircraft type, URET was more accurate than ERAM for over 50% of the aircraft types. This could be caused by possible outliers in the ERAM data since the data was based on its Run-For-Record results and contained some issues that caused outliers. The current version of ERAM may have resolved some of these issues.

An unexpected finding in this study was the limited capabilities of ACES in simulating actual vertical trajectories. There was no known feature in ACES that allowed the user to force a flight to level at given altitudes; as a result, only flights with a continuous ascent to their top of climb were used in the ACES analysis. Also, ACES levels all flights at or near 10,000 feet possibly as a traffic management rule when aircraft are leaving the terminal area. This caused the vertical errors for ACES to be very high. However, RAMS was able to model all types of ascent profiles and, with a mean vertical error of 1,807.6 feet, proved to model trajectories that were almost as accurate as those predicted by the DST URET. When comparing the errors of ACES to those of RAMS, only flights that were in both ACES and RAMS output were considered, and the results showed that the mean vertical error for ACES was 8,195.1 feet while the mean vertical error for RAMS was 1,775.5 feet. This comparison of errors was broken down by aircraft type and it was found that RAMS was more accurate for all of the aircraft types. However, it can not be concluded that this was due to inaccurate aircraft characteristics since the vertical error for each aircraft in ACES was much higher than the errors in RAMS.

Overall, most of our expectations were met. ERAM was as accurate at predicting vertical trajectories as URET and, hence, fulfilled its requirements. RAMS was also proven to be roughly as accurate as URET. Finally, while ACES had high vertical errors, the cause of the errors has been determined, and it seems that if this problem had not occurred, ACES would have much smaller errors.

Acknowledgments

The authors would like to thank Mr. Christopher Hackett and Mr. Chu Yao for their help in the data collection and analyses for this paper. We would also like to thank Mr. Robert Oaks for his skills in supporting the ACES simulations. Finally, we would like to thank Mr. Todd Lauderdale from NASA for addressing our questions about ACES, and Mr. Kenny Martin from ISA Software for his RAMS support.

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